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AIR GUN DEVICES FOR FISH DETERRENCE: PRESSURE FIELD MEASUREMENT AND EVALUATION OF STRUCTURAL EFFECTS

Report No 85-145-K

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ABSTRACT

Pneumatic poppers have been found to be an effective means of reducing fish populations near power plant cooling water intakes. Of concern however, is the effect on the structures of the pressure waves generated by the poppers. This report describes the results of field tests in which the pressure waves generated by popper operation were measured for a variety of geometric configurations and operating conditions. The effect of these pressures on typical civil structures is evaluated in terms of local effects and overall structural response. It is concluded that the operation of low-volume popper devices will not damage typical intake structures.

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EXECUTIVE SUMMARY

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J.D. Tulk and A. Fallis

Pneumatic poppers (air guns) have been found to be an effective tool for reducing the population of fish near the cooling water intakes of electric power stations and consequently reducing both fish mortality and blockage of the cooling system. However, when these devices are operated close to elements of the intake structure, it is important to know whether there is any potential for damage due to the pressure waves. The study described in this report was intended to provide a quantitative description of the pressure wave field due to popper operation and to evaluate the effect on typical intake structures.

The study was based on a series of field tests in which the pressure waves generated by air gun devices were measured in a variety of configurations. These included open water effects (to isolate the effect of wave reflections), tests in the closed forebay area of a power station (where fish mortality experiments were being carried out) and tests with a multi-popper array. These experiments provided the background for a qualitative description of the variation of pressure intensity with distance from the source, the augmentation of pressure due to reflection off of a solid wall and the effect of simultaneous firing of more than one popper.

Based on the experimental pressure data, it is argued that the potential for damage to the heavy concrete structures is very limited. As well, experimental evidence from other sources suggests that there will be no significant damage to open steel structure such as trash racks.

It is concluded that the operation of low volume air guns such as those tested in this project will not harm intake structures.

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To Mr. F.J. Kee
Director of Research

AIR GUN DEVICES FOR FISH DETERRENCE: PRESSURE FIELD MEASUREMENT AND EVALUATION OF STRUCTURAL EFFECTS

1.0 INTRODUCTION

Pneumatic poppers (air guns) can be used effectively to reduce fish density near water intakes of power plants. In this application, groups of poppers are mounted in arrays across the mouth of the intake channel and fired at regular intervals (approximately 15 operations per minute). To provide an adequate deterrent to the fish, it is necessary to generate reasonably intense sound waves. However, before these devices are widely adopted for fish control, it is necessary to determine if their repeated firing can cause damage to the intake structures.

The study described in this report had two main objectives: the quantification of pressure wave characteristics under a variety of operating conditions; and evalulation of the potential for structural damage. The stages in the study were as follows:

Open Field Pressure Measurements

The objective here was to establish the basic form of the pressure waves generated by the poppers at various operating pressures and to determine the relationship between the intensity of the pressure wave and the distance between the popper and the hydrophone (pressure measuring device). These measurements were made in open water to minimize signal distortion due to reflections.

Lennox Forebay Pressure Measurements

A number of pressure measurements were made for air gun devices operating inside the Lennox Generating Station forebay. These measurements were made principally to provide data for the biological experiments being conducted in this area, but were also useful for the study discussed in this report.

Reflected Pulse Measurements

Here the pressure next to a solid concrete wall was measured while a popper was operated at various distances from the wall. These tests measured the intensity of the pressure waves impinging on solid structures, including reflection effects.

Popper Array Measurements

It is expected that practical fish deterrence systems would involve the use of arrays of poppers set up to fire simultaneously. Measurements were taken with various array configurations to check the effect of multiple poppers on the pressure wave intensity and form.

Discussion of Structural Response

Two types of potential damage have been considered in this study. These include large scale effects that would arise from mechanical overload; and local deterioration of concrete due to repeated pressure pulses.

The experiments described in this report were conducted in parallel with a larger experimental program on the effect of poppers on fish populations, conducted by the Biological Research Section of the Ontario Hydro Research Division. The Biological Research Team provided site facilities and much invaluable assistance.

2.0 EXPERIMENTAL APPROACH

The objective of the field experiments was to gather data on popper performance under a variety of conditions. Each experiment consisted of a series of tests in which a popper was suspended underwater and operated while the pressure wave was measured with a sensitive hydrophone and recorded on magnetic tape. Depending on the objectives of the test and the set-up, the popper or the hydrophone would be moved from point to point during testing. As well, the operating pressure of the poppers was varied during the experiments.

Testing was carried out at two sites. The single popper tests were all conducted at Lennox Thermal Generating Station, on the north shore of Lake Ontario about 70 km south-west of Kingston Ontario. This station is not currently operating so that it was possible to have undisturbed access to the cooling water intake and discharge structures. Array tests were conducted at Pickering Nuclear Generating Station, east of Toronto.

2.1 Air Guns

Two air gun devices were used in this study, both from Bolt Technology Ltd. The "MODEL 10", (referred to here as a popper) was used for the majority of the tests. The other device, the "MODEL 10 HYDROADAPTOR", (referred to here as an imploder) was tested over a smaller range of conditions. These devices had been selected by the Biological Research team.

Both air gun devices operate by suddenly releasing a small volume of compressed air. The air was provided to the device from a portable compressor through a flexible hose. The operating pressure referred to in this report is the supply air pressure. The devices were fired by opening a solenoid valve on the body of the gun, which actuated a fast-acting mechanical valve and released a charge of compressed air. The devices were normally operated repeatedly, under the control of an external timer.

At the Lennox test site, the air guns were suspended in the water on the end of a 3 m long aluminum pole. Depending on the test set-up, this pole was supported from part of the forebay or discharge channel structure or from a boat. Because the devices were both relatively small, it was easy to move them about manually between tests. For some of the tests, the popper was positioned manually from a boat. Under these conditions, it was obviously difficult to position the device precisely. For the test at the Pickering test site, an array of poppers was mounted on a rack structure anchored in the intake channel. These poppers could be fired singly or in groups.

2.2 Instrumentation

Instrumentation consisted of a hydrophone (Celesco LC-32), connected, through a 30 m cable to a pre-amplifier (General Radio 1564-A) and tape recorder (Hewlett-Packard 3968). This system was calibrated with equipment traceable to NBS standards.

During the tests, the hydrophone was suspended in the water by its cable. It was positioned manually from the surface. The relative positions of the popper and hydrophone were determined with a measuring tape.

The field test data recordings were analyzed with a digital oscilloscope/waveform analyzer (Data Precision DATA 6000). This instrument was used to determine the amplitude and frequency content of the signals and to prepare the graphs included in this report.

2.3 Test L1 - Open Water Tests

Test L1 was intended to assess the basic characteristics of the popper pressure pulses and to determine the relationship between the intensity of the pressure waves and the distance from the popper. To avoid distortions to the pressure signal that might arise from reflections, this sequence of tests was conducted in open water off the mouth of the discharge channel.

Figure 3 shows a schematic view of the area where the tests were conducted. The popper was suspended from a beam that ran between two concrete breakwater structures, while the hydrophone was positioned from a boat. The arrangement can be seen in the photograph shown in Figure 1. The breakwater structures are visible in the foreground while the instrumentation boat is seen further out in the lake. The hydrophone was suspended from the metal float that can be seen between the boat and the popper.

During these tests, both the popper and hydrophone were suspended about 3.3 m below the surface. The popper was operated continuously, while the hydrophone was positioned at points along a line perpendicular to the shore. The test matrix included five separation distances (0.5 m, 1 m, 2 m, 4 m and 8 m) and three operating pressures (14, 21 and 28 MPa, or 2000, 3000 and 4000 psi). As well, a series of measurements were made with the popper rotated relative to the line of measurement points by 45°, 90° and 180°. (For these tests, the operating pressure was 21 MPa, and the separation distance sequence as above.)

A typical hydrophone signal (pressure pulse time history) is shown in Figure 7, along with its Fourier transform.

The results are summarized in Table 1, which records the peak pressure at the various separation distances, operating pressures and popper orientations. Figure 13 is a log-log plot of peak pressure versus separation distance for following cases:

- popper orientated at 0° and operated at 14 MPa;
- popper orientated at 45° and operated at 21 MPa;
- popper orientated at 90° and operated at 21 MPa; and
- popper orientated at 180° and operated at 21 MPa.

(Data was collected when the popper was orientated at 0° and operated at 21, 28 and 34 MPa. However, the pressures measured in these instances were lower than the corresponding pressures from the 14 MPa tests. On reexamination of the pressure signals, it was noticed that the waveforms for these tests were

more irregular than for the 14 MPa tests (see Figure 8). It was concluded that the poppers were malfunctioning during the tests at higher operating pressures. Intermittent irregularities in popper operation was also noted by the Biological Research team.)

The results from these tests are discussed in Section 3 below.

2.4 Test L2 - Lennox Forebay Tests

This sequence of tests was designed to determine the acoustic pressures from popper and imploder devices, as measured at points in the Lennox forebay structure where the Biological Research team were conducting fish mortality experiments.

Figure 2 is a photograph of the forebay. The air gun devices were mounted adjacent to the dark coloured grating near the centre of the photograph. The round white shapes in the water are nets that were used to confine fish. A schematic layout of the test site is shown in Figure 4.

For the first set of measurements, the popper was suspended 3 m below the surface and operated continuously at 21 MPa. The hydrophone was positioned at a depth of 3 m at net stations located 1, 4, 8, 16, 32 and 50 m from the popper. Next, the popper was replaced by the imploder and the measurements repeated. The results are recorded in Table 2, and plotted in Figure 14.

Figures 9 and 10 show pressure time histories and Fourier transforms for the popper and imploder respectively.

2.5 Test L3 - Reflected Pressure Pulse Measurements

These tests measured the intensity of pressure waves reflected from a solid concrete wall in the centre of the Lennox forebay. Here, the hydrophone was positioned at various locations next to or near the wall and the popper was moved relative to this instrument. Depth was 3 m. The test layout is shown in Figure 5.

Two series of tests were carried out. First, the hydrophone and popper were both located along a line perpendicular to the wall. The parameters varied here were standoff distance (between the hydrophone and wall), separation distance (between the hydrophone and popper) and popper operating pressure. Test results for the first test series are recorded in Table 3A.

For the second series of tests, the hydrophone was suspended 2 m from the wall. The popper was positioned at points along a line originating from the popper, parallel to the wall.

Figure 11 shows a pressure time history measured with the hydrophone against the wall and the popper approximately 0.5 m away. Comparison with the open water tests (Figure 7) shows that the signature is similar to that recorded earlier, but that the amplitude of the pressure pulse is higher, apparently because of the strong reflection from the solid wall. The relationship between amplitude and distance is shown in Figures 15 and 16. Figure 15 shows the intensity of the incident plus reflected waves, as measured at various distances from the wall, while Figure 16 compares the pressure/distance relationship for the combined incident-reflected wave (ie, hydrophone on wall) and the open water measurements.

2.6 Test P1 - Popper Array Measurements

The sound source for these tests was an array of twelve poppers suspended from a rack structure that was anchored at the mouth of the intake channel of the Pickering generating station (see Figure 6). The popper array consisted of three horizontal rows of four poppers, stacked vertically at depths of 1.5, 3 and 4.5 m. The poppers could be operated singly or in groups and the test matrix included 1, 2, 4 and 8 popper groups. The hydrophone was suspended at a depth of 3 m and moved on a line perpendicular to the plane of the popper array. Measuring distances were 1, 2, 4, 8, 16 and 32 m.

Results of these tests are recorded in Table 4 and in Figures 12 (sample time history) and 17 (pressure/distance plot).

3.0 DISCUSSION OF RESULTS

3.1 Air Gun Characteristics

The pressure time history recorded for the single popper operating in open water (Figure 7) shows the characteristic "signature" for this type of air gun. There is a brief, sharp pulse, followed by an oscillating signal that resembles a decaying sinusoid. The frequency of the sinusoidal part of the signal was approximately 70 Hz, as shown on the Fourier transform. It appears that the initial pulse is due to the first release of compressed air, while the oscillating part of the signal was due to "ringing" in the chamber of the popper.

Pressure pulse signatures for the forebay tests (Figure 9) and reflected wave tests (Figure 11) are very similar to the open water signatures. This seems reasonable if we consider the basic characteristics of sound wave propagation in water. The speed of sound in fresh water is approximately 1444 m/s. Thus, if there are reflecting obstacles within a few metres of the popper or hydrophone, the reflected component of the signal will

arrive within a few milliseconds of the directly transmitted wave. The reflected component will have the same signature as the direct wave but a smaller amplitude because of losses on reflection and because it will have to travel further. The hydrophone will pick up the superimposed combination of the direct wave and the delayed and attenuated reflected wave. Provided that the time delay for the reflected wave is small compared to the period of the signal, the shape of the combined signal will not be significantly distorted. Reflections from more distant objects or surfaces will have a greater phase shift, but because of attenuation with distance, will have lower amplitudes.

The multi-popper array test yielded a similar time history signature. This suggests that the poppers fired nearly simultaneously and that the signals from the different poppers were substantially similar in signature.

The pressure time history recorded from the imploder device is distinctly different from the popper signal (compare Figures 9 and 10). The imploder signature consists of an initial drop in pressure for about 5 ms, followed by a short, sharp, positive pulse and a period of relatively low amplitude noise. Comparison of the Fourier transforms confirms that the imploder signal is less strongly periodic than the popper signal. The peak pressure level of the imploder signal was notably higher than that of the popper.

3.2 Pressure-Distance Relationships

Figures 13 to 17 are plots of the peak pressure versus distance for the various tests carried out as part of this program. In almost all cases, the data can be fitted to a straight line on the log-log plot. This implies an empirical pressure-distance relationship of the form:

$$P(r) = \frac{P_o}{r^{\gamma}} \qquad (1)$$

where:

$P(r)$ is peak pressure;
P_o is peak pressure, normalized at 1 m;
r is the distance from the air gun; and
γ is an empirically determined number between 0.9 and 1.4

Theory states that a spherical acoustic source will produce a wave that attenuates inversely with radius in an infinite space

(cf. Reference 2, Chapter 7). That is, in an infinite, unobstructed body of water, the exponent "γ" in this equation would equal one. However, where there are reflections from surfaces (such as the bottom or the air-water interface), or from other objects, the rate of attenuation with distance will change. For example, in Reference 2, chapter 15, it is demonstrated that waves from an acoustic source will attenuate more rapidly when the source is just below the surface and the exponent "γ" will take a value between one and two. Thus, the empirically based pressure-displacement relationship given in Equation (1) is consistent with theory.

3.3 Effect of Popper Orientation

The body of the popper was cylindrical in shape, with the exhaust port located on one side. It seemed plausible that the pressure waves would be more intense along a radius originating from this port than at other positions around the popper and tests were conducted to determine whether or not the pressure field produced by the popper was axisymmetric.

These tests were included in test series L1, the open water tests. The procedure was to rotate the body of the popper in the water, then to record pressure pulses at the points indicated in Figure 3.

The results are shown in Figure 13 which compares the relationship between pressure and distance for a number of orientations. The results of this test is not entirely conclusive as there is some concern as to whether the popper was operating at full efficiency during the tests when the operating pressure was 21 MPa. The test results suggest however that variations of pressure with direction are minor compared to variations with distance. The popper was apparently operating consistently during the 45, 90 and 180° tests and there is no significant difference between the recorded peak pressures.

3.4 Effect of Operating Pressure

As was noted above, the results of the open water tests with higher operating pressures are ambiguous because of apparent popper malfunction. However, during the tests adjacent to the solid wall (test series L3), the popper was running properly at all pressures. Thus, the effect of operating pressure changes can be evaluated from Figure 15.

On the basis of test L3 results, the acoustic pressure varies with operating pressure, but only slowly. An increase in operating pressure to 21 MPa from 14 MPa increased the acoustic pressure by about 13%. A further increase in operating pressure

to 28 MPa lead to acoustic pressures about 20% above the level recorded for 14 MPa operation.

3.5 Popper Versus Imploder

A comparison of acoustic pressure amplitude for the popper and imploder devices is shown in Figure 14. Clearly, the imploder device produces significantly higher peak pressures than the popper. At an operating pressure of 17.5 MPa and a distance of 1 m, the imploder signal had a peak of 65 kPa. In comparison, the popper, operating at 21 MPa, produced a peak pressure at 1 m of 19 kPa.

3.6 Reflection Effects

Acoustic theory predicts that when a wave reflects from a solid wall (as in Test L3), the incident and reflected waves will interfere constructively and the pressure amplitude measured at the wall will be twice the amplitude of a wave from the same source, measured in open water. Figure 16 compares these two conditions and confirms this relationship.

3.7 Multi-Popper Operation

The pressure pulse generated by an array of poppers will be the summation of the signals from each gun. If the poppers are closely spaced and are fired synchronously, phase shift effects will be minor and the pressures can be added directly. Of course, the summation must take into account the relative distances of each of the poppers from the hydrophone. Generalizing equation (1) above, the peak pressure from an array will be expressed by the equation:

$$P = \sum_{i=1}^{n} \frac{P_o}{r_i^{\gamma}}$$

where:

n is the number of poppers; and
r_i is the distance between the hydrophone and the ith popper.

This relationship is consistent with the experimental results shown in Figure 17. The theory curves assume a "γ" of 1.25. Where the hydrophone is far from the popper array, all of the poppers are at a relatively even distance and the pressure peak of the array approaches eight times the amplitude of the signal from a single device. However, closer to the poppers, the contribution of poppers at the edge of the array is relatively weak

(since they are farther from the hydrophone) so that the array signal is a smaller multiple of the signal from the single popper.

4.0 STRUCTURAL EFFECTS

We will consider two types of structural damage that might be caused by the operation of nearby underwater air guns: local degradation of concrete surfaces and larger scale structural damage due to overloading. In each case, we will consider the effect of a single device (popper or imploder) operating as close as 0.5 m from the structure. The pressure levels and signatures are based on the experiments described above.

4.1 Local Effects

Test series L3 measures pressures at the surface of a solid wall. As is shown in Table 3A, the peak pressure recorded for a popper operating at the maximum line pressure (28 MPa), one half metre from the wall was 60.9 kPa (8.8 psi). The compressive strength of concrete is typically between 21 and 28 MPa (3000 to 4000 psi)/3/ so that there is no danger of local concrete failure in direct compression due to popper operation.

We have no experimental data on the operation of the imploder device close to a solid wall so that an assessment of possible damage by this type of air gun will have to be based on an extrapolation of the data available. Theory and Figure 16 both indicate that the pressure intensity on an unyielding reflecting surface will be twice the pressure measured in open water. The peak pressure for the imploder was measured to be 65 kPa at a distance of 0.5 m in open water (cf, Table 2 and Figure 14). Thus the peak pressure on a wall would be approximately 130 kPa (19 psi). Again this is far below the compressive strength of typical concrete.

A literature search was conducted to find information on the effects of fluctuating pressures on concrete surfaces (References 3 to 6). The main pressure-related problem that was identified was due to cavitation effects in high velocity flows. As is shown below, the dynamic pressures due to popper or imploders operations are too small to initiate cavitation.

Cavitation occurs when the local hydraulic pressure falls below the vapour pressure at that temperature so that bubbles of water vapour form next to the concrete surface. If the pressure fluctuates quickly (due to turbulent flow conditions for example) these bubbles can collapse and cause very high instantaneous impact pressures as the water rushes in to re-occupy the space/4/. The result can be a very rapid erosion of the surface/5,6/.

Cavitation requires that the absolute pressure fall below vapour pressure, which lies between 0.5 and 4.2 kPa depending on water temperature. The minimum relative pressure recorded during our tests was approximately -24 kPa (Test L3, Figure 11). However, the static pressure for the location where the pressure measurement was made was approximately 131 kPa, due a combination of atmospheric pressure (101 kPa) and 3 m of water. Thus, the absolute pressure was at least 106 kPa and there is no possibility of cavitation on the surface of the concrete due to poppers.

Negative pressures generated by the imploder device were similar in magnitude to the negative pressures of the popper (compare Figures 9 and 10). Thus there is no realistic possibility of cavitation on the concrete face due to imploder operation.

We conclude that there is no danger that either of the devices tested in this program would cause local damage to a sound concrete surface if they operated at a distance of at least 0.5 m from the surface.

4.2 Large Scale Structural Response

Structural damage would be caused by the poppers if the dynamic response of the structure exceeds safe limits. What is safe in a particular situation will depend on the details of the structure, but it is often assumed that if the peak response velocity is less than two inches per second (50 mm/s), the structure will generally be safe/7,8/.

The following calculations are intended to provide a very conservative estimate of the dynamic response of a typical heavy concrete structure, such as would be found in a power plant intake.

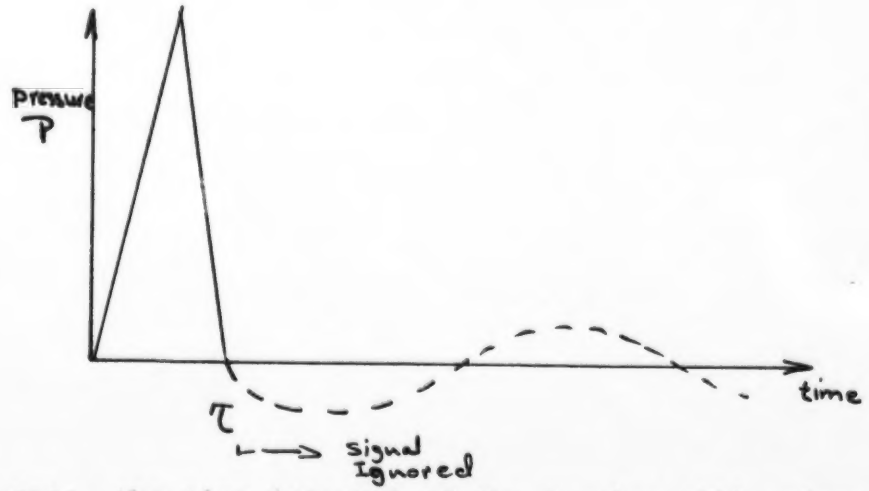
Clough and Penzien/9/ suggest that for structures where the period of vibration is long relative to the duration of the forcing function, reasonable estimates of the structural response can be made by an approximate impulse response analysis. This analysis is based on the simple formula:

$$\Delta V = \frac{1}{m} \int_0^{\tau} F(t)dt \qquad (3)$$

where:

ΔV is the velocity increment due to the impulsive load;
$F(t)$ is the force function;
m is the mass of the structure; and
τ is the duration of the impulse.

Assuming that the most important part of the pressure signal for either the poppers or imploder is the initial positive pulse, then both can be reduced to simple triangular time histories.



In this case, the time integral of the impulse will reduce to a simple formula:

$$\int_0^{\tau} F(t)dt = \frac{1}{2} F_{max}\tau \qquad (4)$$

where:

τ is the duration of the triangular pulse

Referring back to equations 3:

$$\Delta V = \frac{1}{2m} \cdot F_{max}\tau$$

Assume, for simplicity (and conservativeness) that the pressure is uniform over a "unit area" (1 m^2). Thus, the force is numerically equal to the pressure. Assume further that the mass in question is a cube of concrete 1 m on each side. Numerically then:

$$F_{max} = P_{max} = 60.9 \text{ kPa}$$

$$\tau = 0.0025 \text{ s}$$

$$m = 2200 \text{ kg}$$

Than V = 35 mm/s (1.4 in/s), which is less that the 2 in/s criterion cited above. For an imploder:

$$F_{max} = P_{max} = 130 \text{ kPa}$$

$$\tau = 0.001 \text{ s}$$

$$m = 2200 \text{ kg.}$$

Thus, V = 30 mm/s (1.2 in/s).

These calculations are obviously very approximate and simplified, but do indicate that the effect of the very short duration pressure pulses due to popper or imploder operations will not cause a significant level of response in massive concrete structures.

Steel structures such as trash racks are much lighter than concrete structures and might be expected to respond more readily to short duration pressure pulses. However, the effect of a pressure wave on this type of structure is rather complex because of the open geometry. In this case, rather than attempt analysis, we refer the reader to a study on the use of air guns for control of ice build-up on trash racks/8/. In this study, pressures and response velocities were measured on a trash rack while various sizes of air guns were operated nearby. The air guns used were similar in design to the poppers proposed for fish control, but had rather larger air chambers and produced stronger pressure pulses. It was found that for air guns with air chamber volumes less than 50 cubic inches, pressure pulses with peak amplitudes as high as 120 kPa (18 psi) produced response velocities that were less than 25 mm/s. Since the pressure amplitudes are larger than the pressures generated by the relatively small fish control poppers, while the vibrations were still within reasonable limits, it seems reasonable to assume that popper operation would not damage trash racks.

We cannot entirely rule out the possibility that the pressure pulses produced by poppers could damage some structures. However, the loads are generally small compared to the other operating loads due to hydrostatic pressure, winter ice and other commonly encountered hazards. Since intake structures are generally massive and robust, we conclude that the actual probability of damage is very small.

5.0 CONCLUSIONS

The pressure measurements reported here provide a clear picture of the underwater acoustic pressure field produced by the Bolt

Technology "MODEL 10" popper and "MODEL 10 HYDROADAPTOR" imploder devices used in the fish deterrence experiments. The main features are:

- Each device has a characteristic signature. Firing a popper produces a brief initial pulse (about 0.0025 s in duration) followed by a decaying periodic signal with a natural frequency of about 70 Hz. An imploder produces a very short, intense pulse that is followed by low amplitude noise.

- The pressure amplitude of the signal attenuates with distance according to the formula

$$P(r) = \frac{P_o}{r^{\gamma}}$$

  where γ is equal to about 1.25.

- When the signal is reflected from a solid wall, the pressure measured on the surface is doubled, as compared to the pressure that would occur in open water.

- The pressure level produced by the firing of several poppers simultaneously can be estimated by summing the effects of each popper operating separately.

It is highly improbable that the operation of small poppers for fish control will cause damage to sound concrete surfaces or to massive concrete structures. Available test results imply that the small volume poppers used in these tests will not damage steel structures such as trash racks or screens.

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TABLE 1

PNEUMATIC POPPER ACCOUSTIC TESTS

Test: L1 - Lennox TGS Discharge Bay
Date: August 15, 1984
Source: "Model 10" Popper
Depth: 3.3 meters

Separation m	Operating Pressure MPa	Source Orientation deg	Acoustic Pressure Peak kPa	psi	dB re 1uPa	Fund Freq Hz
.5	14	0	31	4.5	183	70
1	14	0	12.3	1.8	177	70
2	14	0	2.8	.4	160	70
4	14	0	1.6	.2	156	4
8	14	0	1.0	.2	145	4
.5	21	0	12.2	1.8	175	70
1	21	0	7.9	1.2	168	70
2	21	0	1.5	.2	162	16
4	21	0	.9	.1	161	0
8	21	0	.8	.1	151	12
.5	34	0	11.5	1.7	173	31
1	28	0	8.3	1.2	170	15
2	28	0	2.4	.4	166	15
4	28	0	.8	.1	163	20
8	28	0	.5	.1	157	0
.5	21	45	22.0	3.2	184	66
1	21	45	11.5	1.7	174	66
2	21	45	3.7	.5	163	15
4	21	45	.7	.1	160	19
8	21	45	.5	.1	154	0
.5	21	90	22.0	3.2	181	66
1	21	90	10.2	1.5	177	66
2	21	90	2.6	.4	163	19
4	21	90	1.0	.2	160	19
8	21	90	.3	.1	157	0
.5	21	180	21.0	3.2	179	66
1	21	180	8.5	1.3	169	66
2	21	180	2.8	.4	166	19
4	21	180	.8	.1	159	12
8	21	180	.7	.1	153	12

TABLE 2

PNEUMATIC POPPER ACCOUSTIC TESTS

Test: L2 - Lennox TGS Forebay
Date: August 27-28, 1984
Source: "Model 10" Popper, "Model 10 Hydroadaptor" Imploder
Depth: 3 meters

Source	Separation m	Operating Pressure MPa	Acoustic Pressure Peak kPa	psi	dB re 1uPa	Fund Freq Hz
Popper	1	21	19	2.8	184	47
"	4	21	4.2	.6	175	47
"	8	21	2.2	.3	168	47
"	16	21	1.0	.2	157	47
"	32	21	.5	.1	153	51
"	50	21	.3	.1	153	51
Imploder	1	17.5	65.0	9.4	180	107
"	4	17.5	19.6	2.8	174	107
"	8	17.5	7.4	1.1	167	136
"	16	17.5	2.8	.4	160	105
"	32	17.5	2.0	.3	155	941
"	50	17.5	.9	.1	148	54

TABLE 3A

PNEUMATIC POPPER ACCOUSTIC TESTS

Test: L3.1 - Lennox TGS Forebay
Date: October 10, 1984
Source: "Model 10" Popper
Depth: 3 meters

Separation Dstance *1 m	Standoff Distance *2 m	Operating Pressure MPa	Acoustic Pressure Peak kPa	psi	dB re 1uPa	Fund Freq Hz
.5	0	14	54.4	7.9	201	58
1	0	14	22.2	3.2	193	58
2	0	14	9.5	1.4	183	58
.5	0	21	59.7	8.7	203	49
1	0	21	25.4	3.7	194	58
2	0	21	11.7	1.7	188	58
.5	0	28	60.9	8.8	201	39
1	0	28	29.3	4.3	197	49
2	0	28	11.7	1.7	188	49
.5	.5	14	26.7	3.9	195	58
1	.5	14	11.1	1.6	187	58
2	.5	14	5.3	.8	187	58
.5	.5	21	30.1	4.4	195	58
1	.5	21	18.2	2.6	192	58
2	.5	21	8.2	1.2	182	49
.5	.5	28	35.4	5.1	200	49
1	.5	28	17.1	2.5	193	49
2	.5	28	9.4	1.4	187	49
.5	1	14	32.6	4.7	197	58
1	1	14	19.1	2.8	193	58
2	1	14	7.3	1.1	182	58
.5	1	21	33.6	4.9	196	49
1	1	21	11.8	1.7	188	49
2	1	21	7.7	1.1	183	49
.5	1	28	20.7	3.0	196	49
1	1	28	27.3	4.0	198	49
2	1	28	8.2	1.2	187	49
.5	2	14	39.8	5.8	195	58
1	2	14	18.7	2.7	190	58
2	2	14	6.4	.9	181	58
.5	2	21	54.9	8.0	200	58
1	2	21	24.2	3.5	195	58
2	2	21	10.0	1.5	184	61
.5	2	28	25.9	3.8	195	49
1	2	28	11.6	1.7	189	49
2	2	28	8.8	1.3	185	57

*1 - Popper-Hydrophone *2 - Wall-Hydrophone

TABLE 3B

PNEUMATIC POPPER ACCOUSTIC TESTS

Test: L3.2 - Lennox TGS Forebay
Date: October 10, 1984
Source: "Model 10" Popper (Oriented 90 deg to wall)
Depth: 3 meters

Separation D1*1 m	Separation D2*2 m	Operating Pressure MPa	Acoustic Pressure Peak kPa	psi	dB re 1uPa	Fund Freq Hz
.5	2	14	47.3	6.9	198	58
1	2	14	19.3	2.8	192	58
2	2	14	6.5	.9	183	58
.5	2	21	44.1	6.4	199	58
1	2	21	22.9	3.3	195	58
2	2	21	10.3	1.4	189	58
.5	2	28	37.6	5.5	202	49
1	2	28	32.0	4.6	199	49
2	2	28	9.9	1.4	189	49

TABLE 4

PNEUMATIC POPPER ACCOUSTIC TESTS

Test: P1.1 - Pickering NGS Inlet bay (West Diversion Platform
Date: August 24, 1984
Source: "Model 10" Popper
Depth: 3 meters
Operating Pressure: 17.5 MPa

Separation m	Poppers Operating	Acoustic Pressure Peak kPa	psi	dB re 1uPa	Fund Freq Hz
1	No 5	9.9	1.4	178	55
1	Nos 2 & 11	5.4	.8	176	50
1	Nos 1,3,11,12	5.0	.7	175	55
1	Nos 2,4,5,6,7, 8,9 & 11	23.9	3.5	191	51
2	No 5	4.0	.6	173	55
2	Nos 2 & 11	3.7	.5	177	55
2	Nos 1,3,11,12	6.9	1.0	176	51
2	Nos 2,4,5,6,7, 8,9 & 11	19.1	2.8	186	51
4	No 5	2.2	.3	165	55
4	Nos 2 & 11	4.1	.6	169	55
4	Nos 1,3,11,12	4.7	.7	172	55
4	Nos 2,4,5,6,7, 8,9 & 11	10.7	1.6	180	51
8	No 5	.9	.1	154	55
8	Nos 2 & 11	1.3	.2	158	59
8	Nos 1,3,11,12	2.7	.4	164	55
8	Nos 2,4,5,6,7, 8,9 & 11	5.7	.8	167	51
16	No 5	.8	.1	149	4
16	Nos 2 & 11	.8	.1	154	59
16	Nos 1,3,11,12	1.3	.2	155	59
16	Nos 2,4,5,6,7, 8,9 & 11	2.6	.4	161	51
32	No 5	.4	.1	146	4
32	Nos 2 & 11	.8	.1	144	4
32	Nos 1,3,11,12	.7	.1	149	51
32	Nos 2,4,5,6,7, 8,9 & 11	2.3	.3	154	51

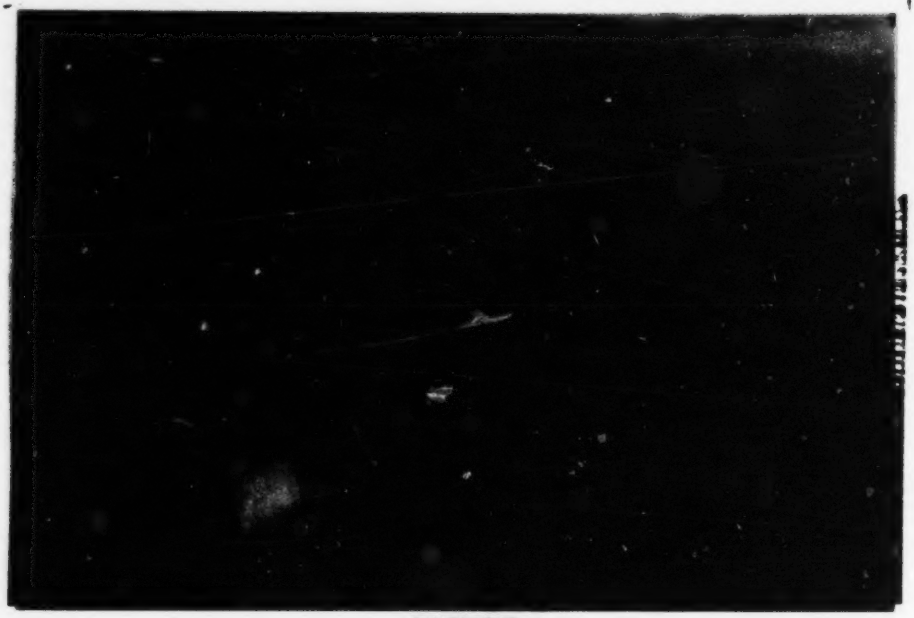


FIGURE 1

OPEN WATER TEST (L1);
LENNOX DISCHARGE CHANNEL

FIGURE 2

LENNOX FOREBAY
TESTS (L2)

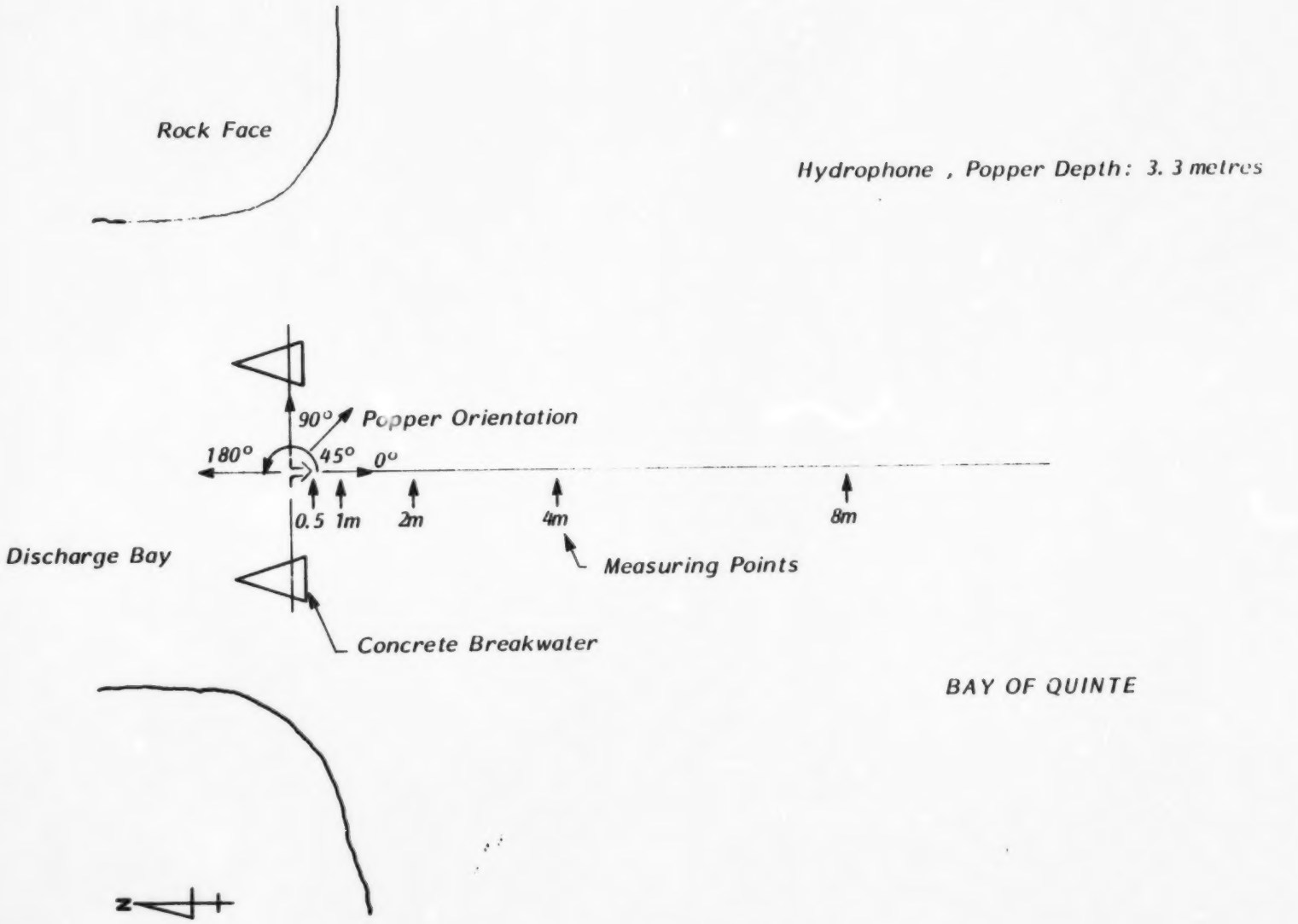


FIGURE 3

LENNOX TGS DISCHARGE CHANNEL
SITE OF TEST L1

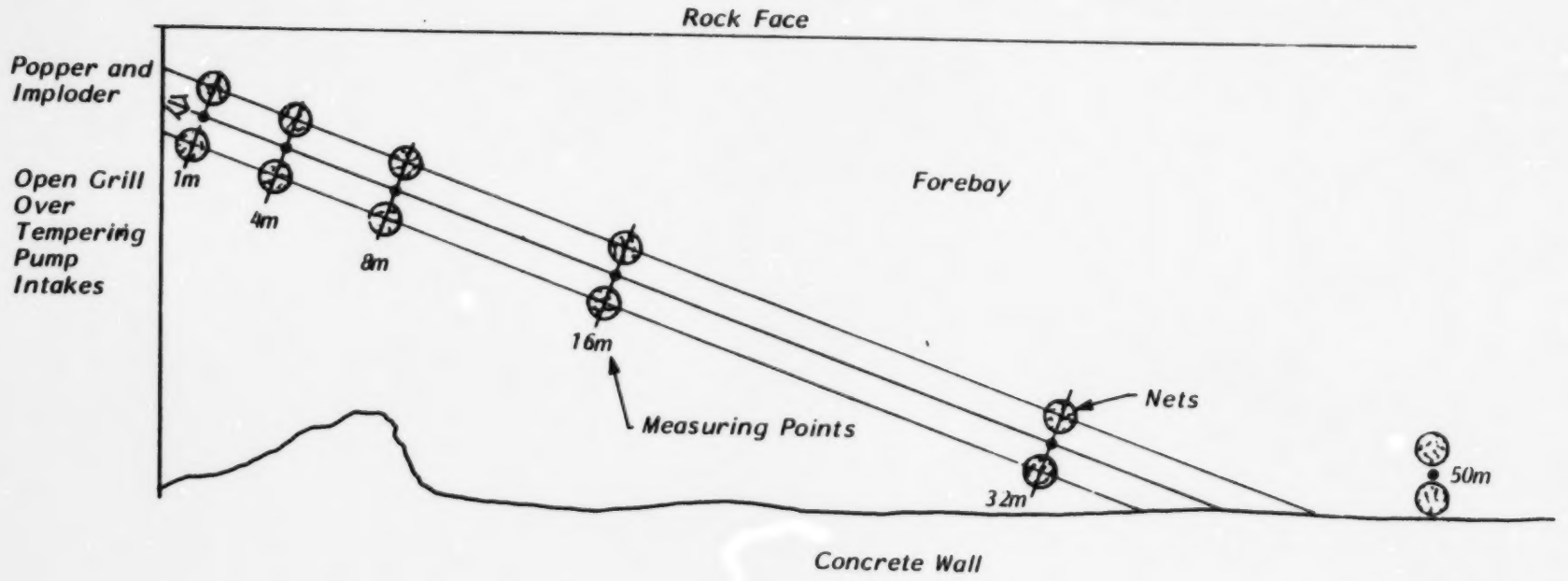


FIGURE 4

LENNOX FOREBAY
SITE OF TEST L2

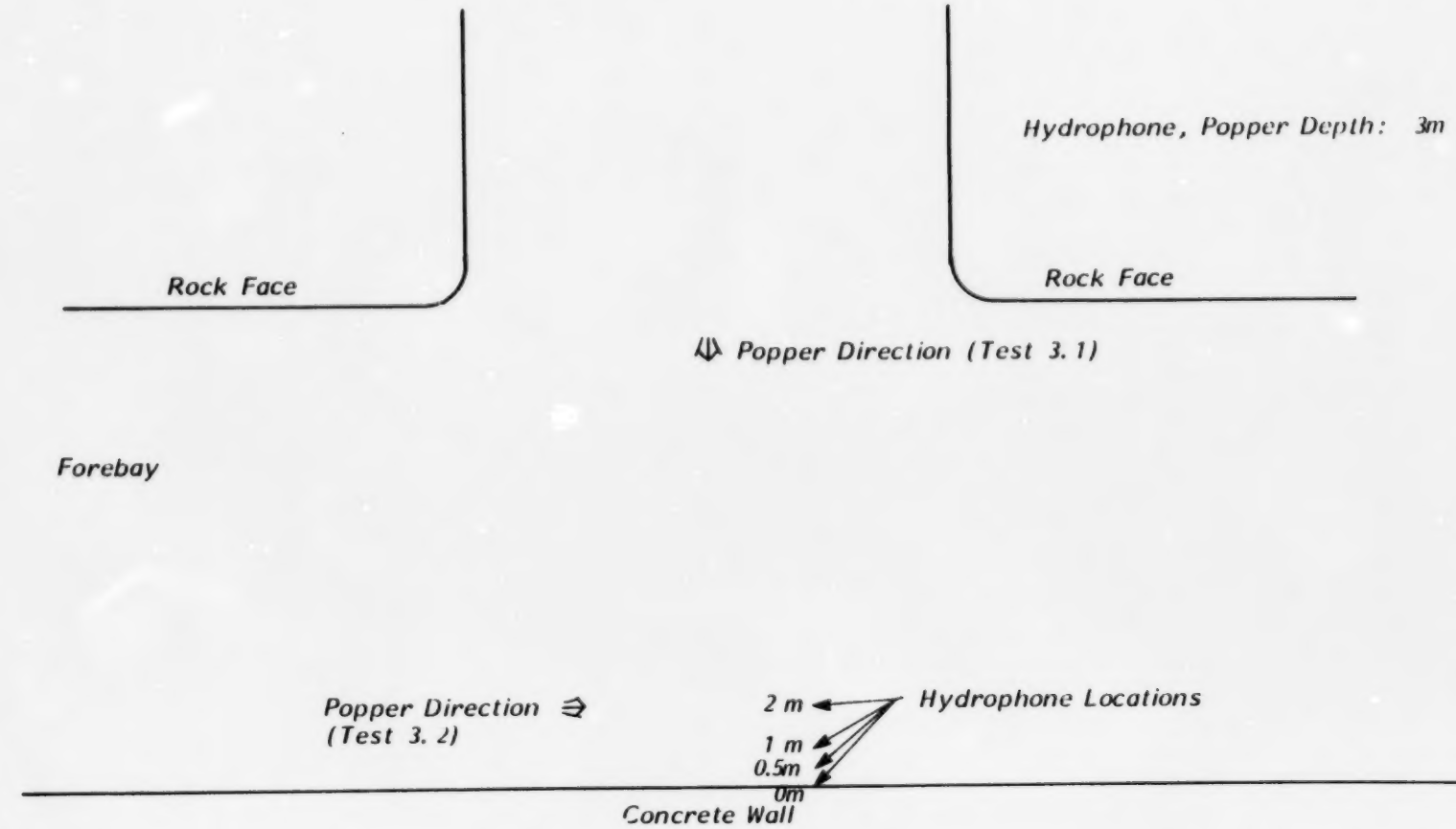
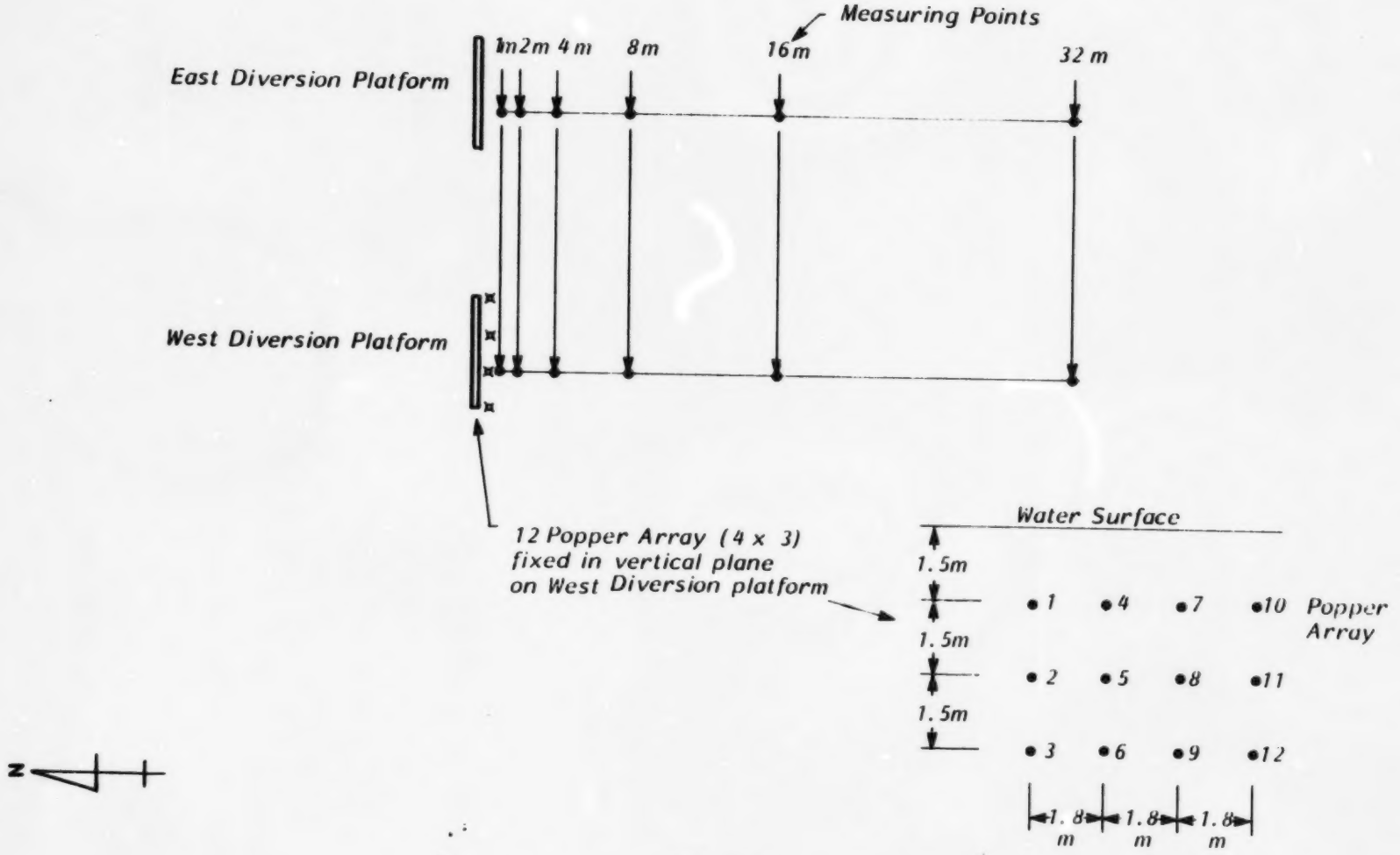


FIGURE 5

LENNOX FOREBAY
SITE OF TEST L3

Hydrophone Depth: 3 m (aligned with popper #5



FICURE 6

PICKERING INLET CHANNEL
SITE OF TEST P1

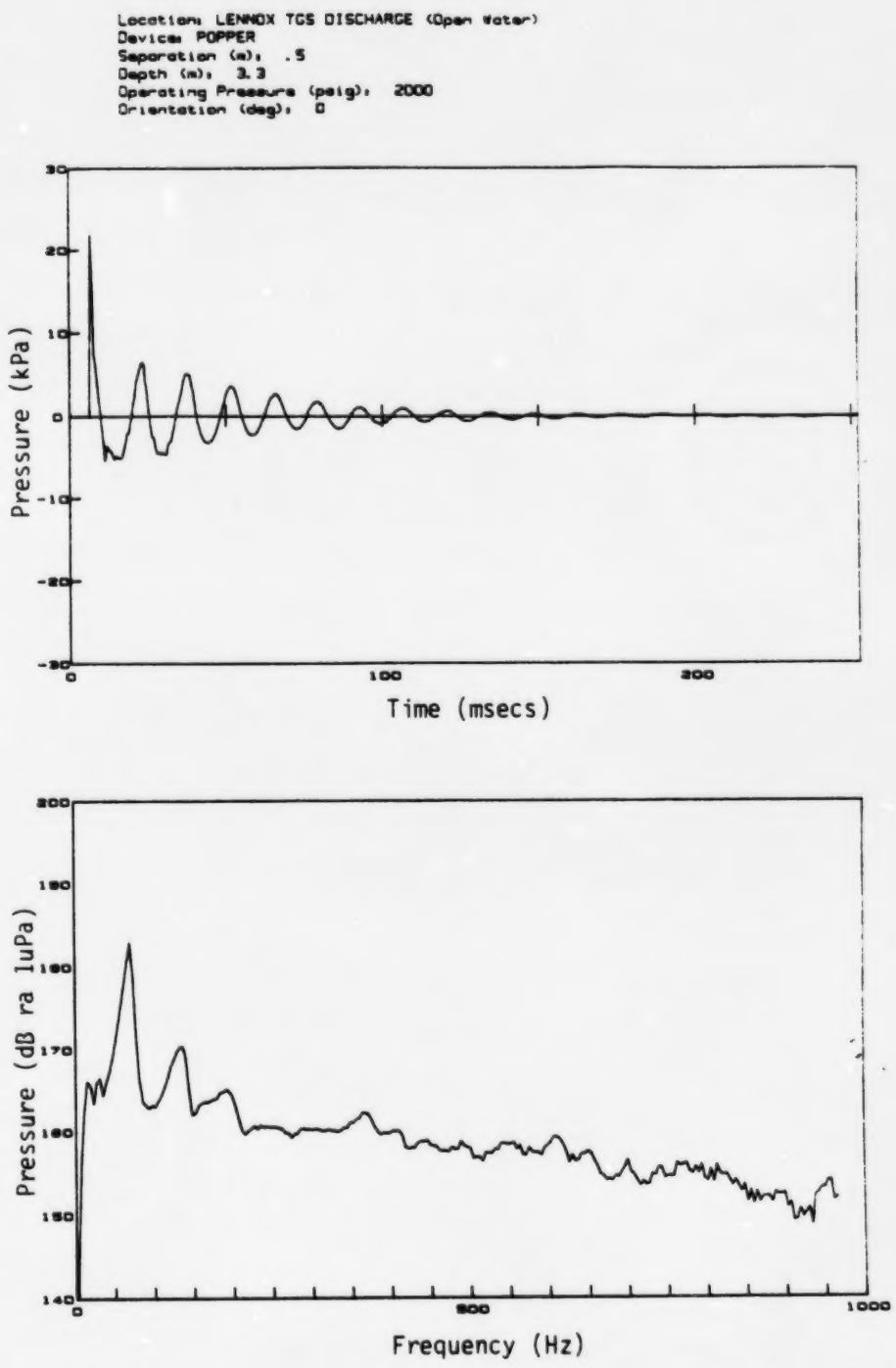


FIGURE 7

SAMPLE PRESSURE PULSE
TEST L1

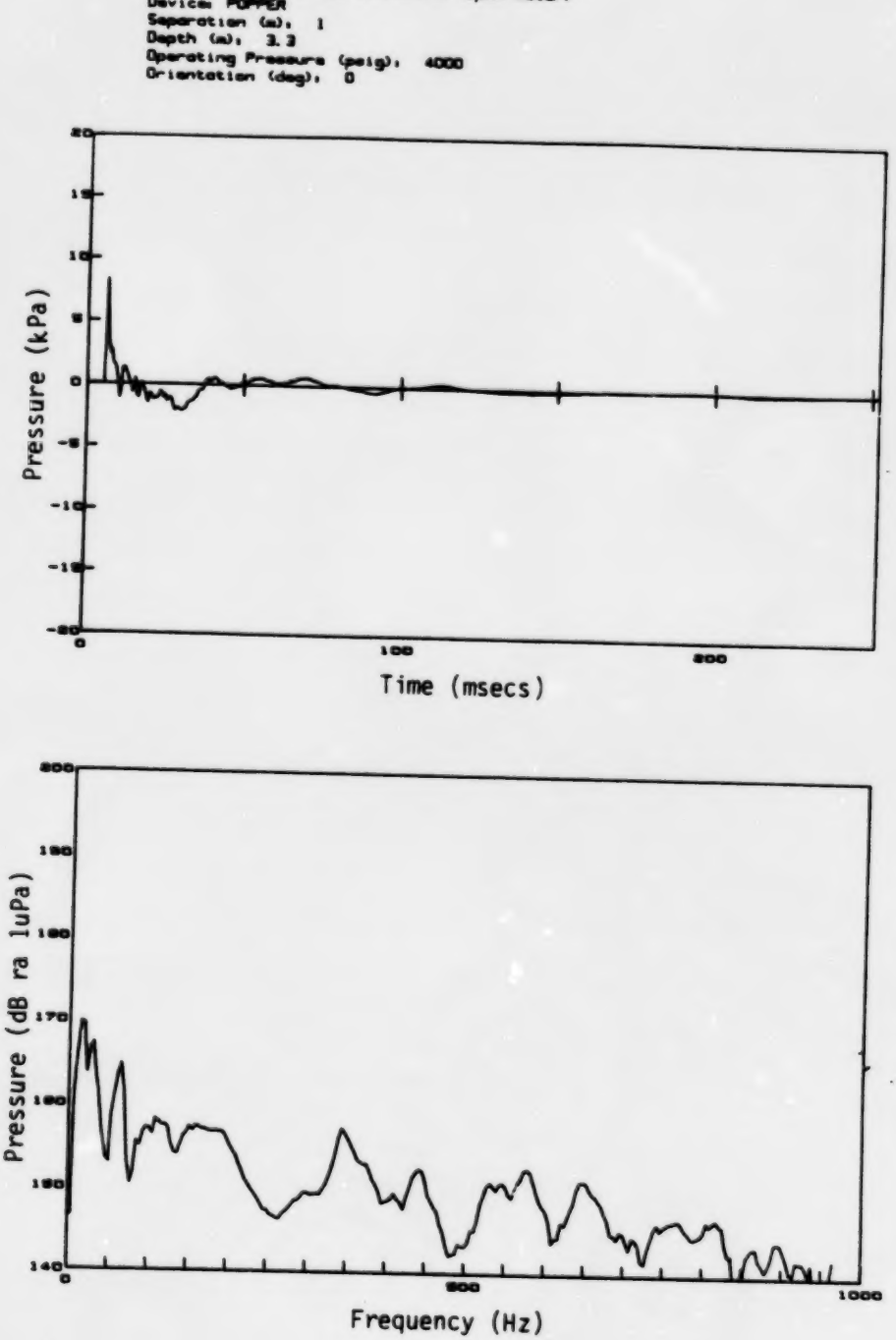


FIGURE 8

SAMPLE PRESSURE PULSE
TEST L1 - MALFUNCTIONING POPPER

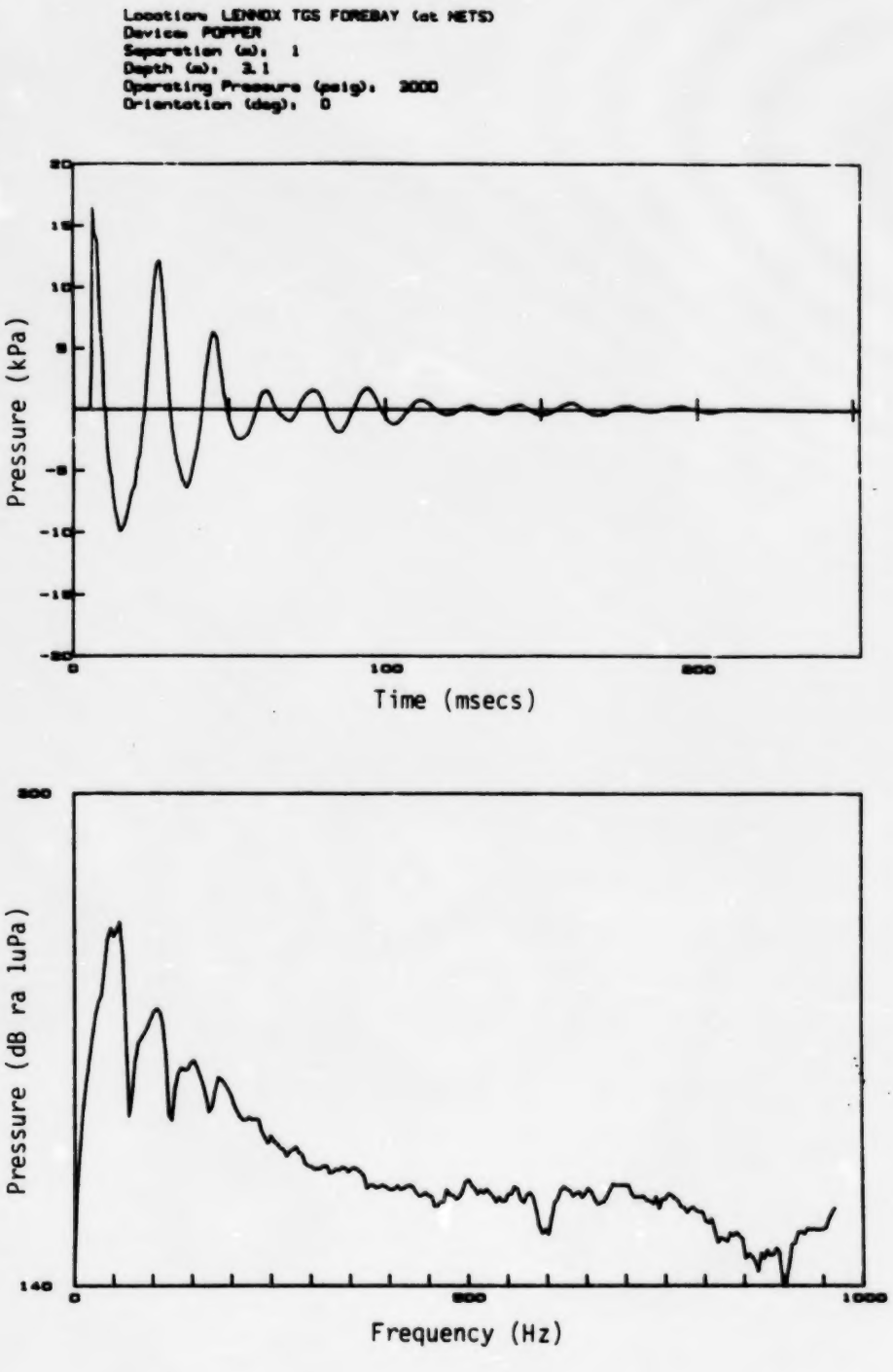


FIGURE 9

SAMPLE PRESSURE PULSE
TEST L2 - POPPER

168214 RD

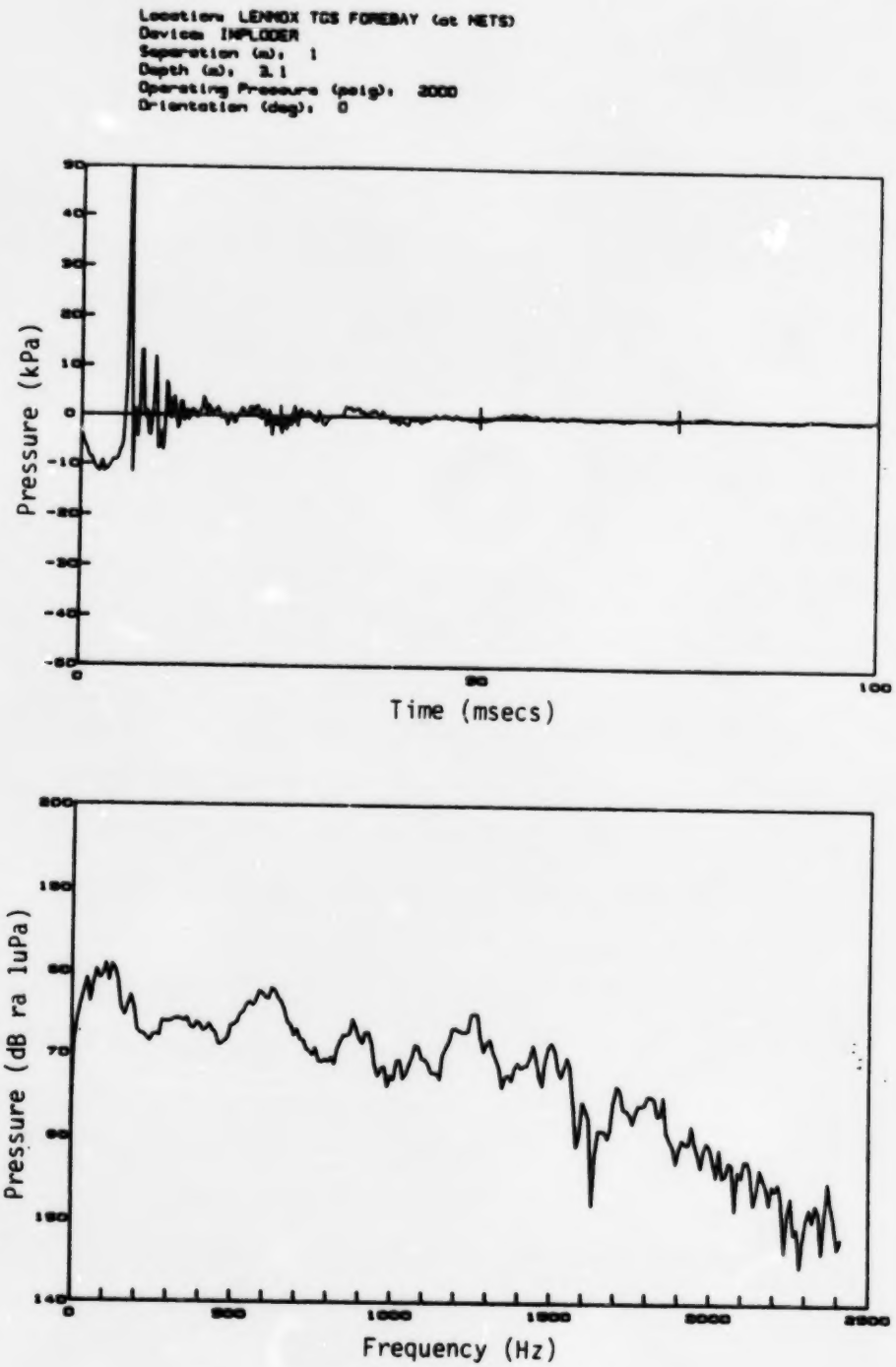


FIGURE 10

SAMPLE PRESSURE PULSE
TEST L2 - IMPLODER

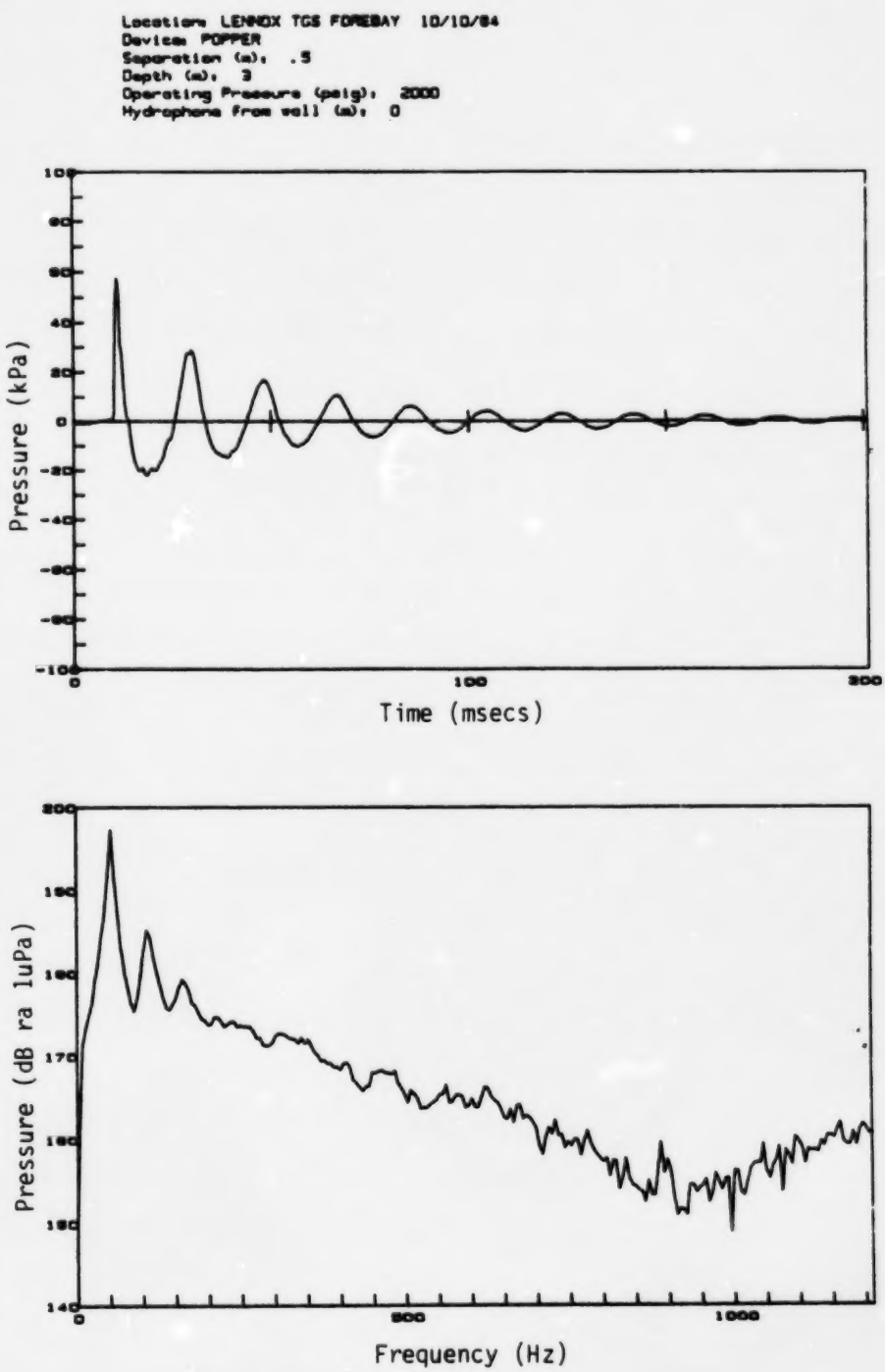


FIGURE 11

SAMPLE PRESSURE PULSE
TEST L3 - REFLECTED WAVE

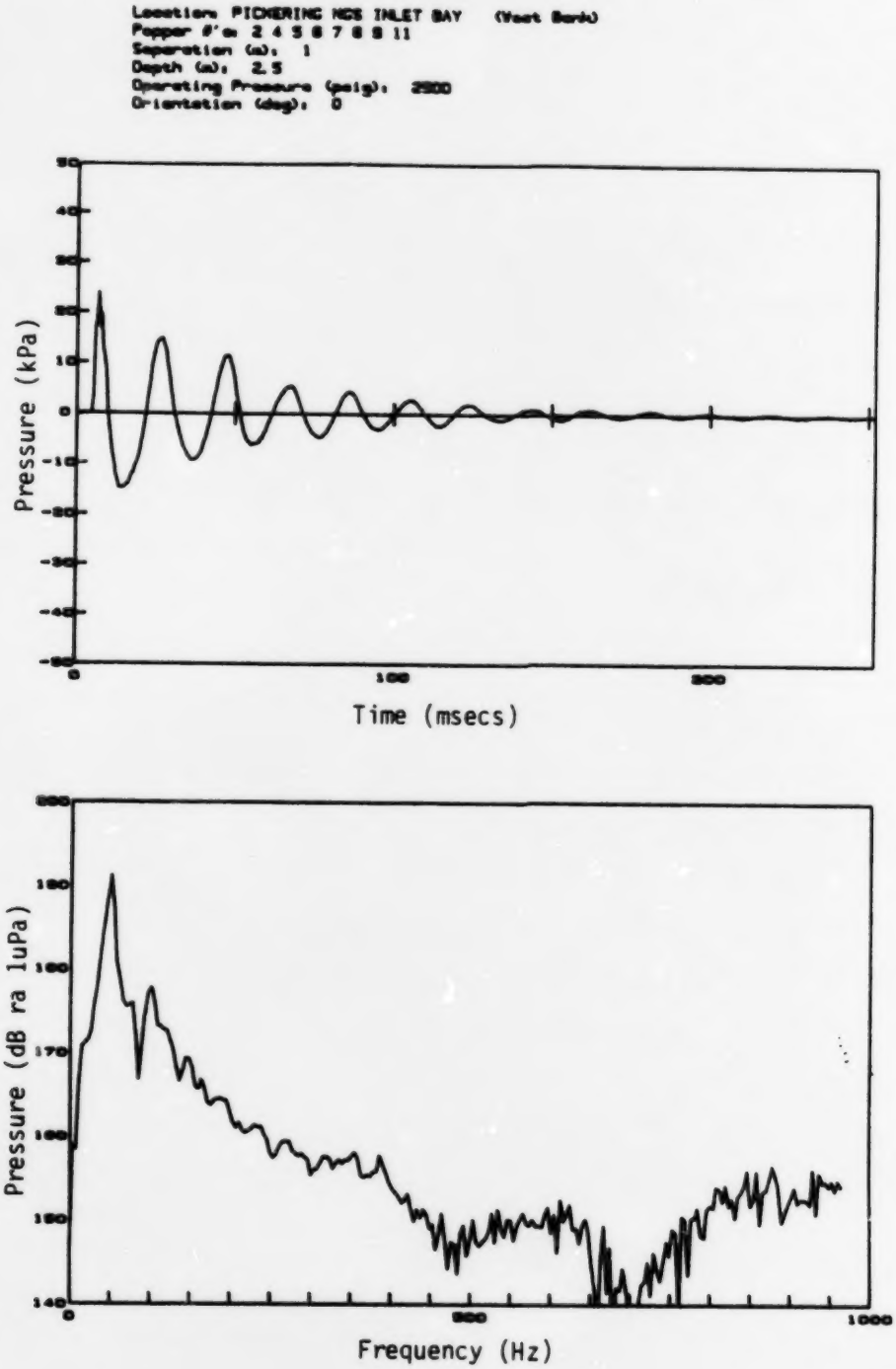

Location PICKERING NGS INLET BAY (West Bank)
Popper #'s 2 4 5 6 7 8 9 11
Separation (m): 1
Depth (m): 2.5
Operating Pressure (psig): 2500
Orientation (deg): 0
Pressure (kPa)
Time (msecs)
Pressure (dB re 1uPa)
Frequency (Hz)

FIGURE 12

SAMPLE PRESSURE PULSE
TEST P1 - POPPER ARRAY

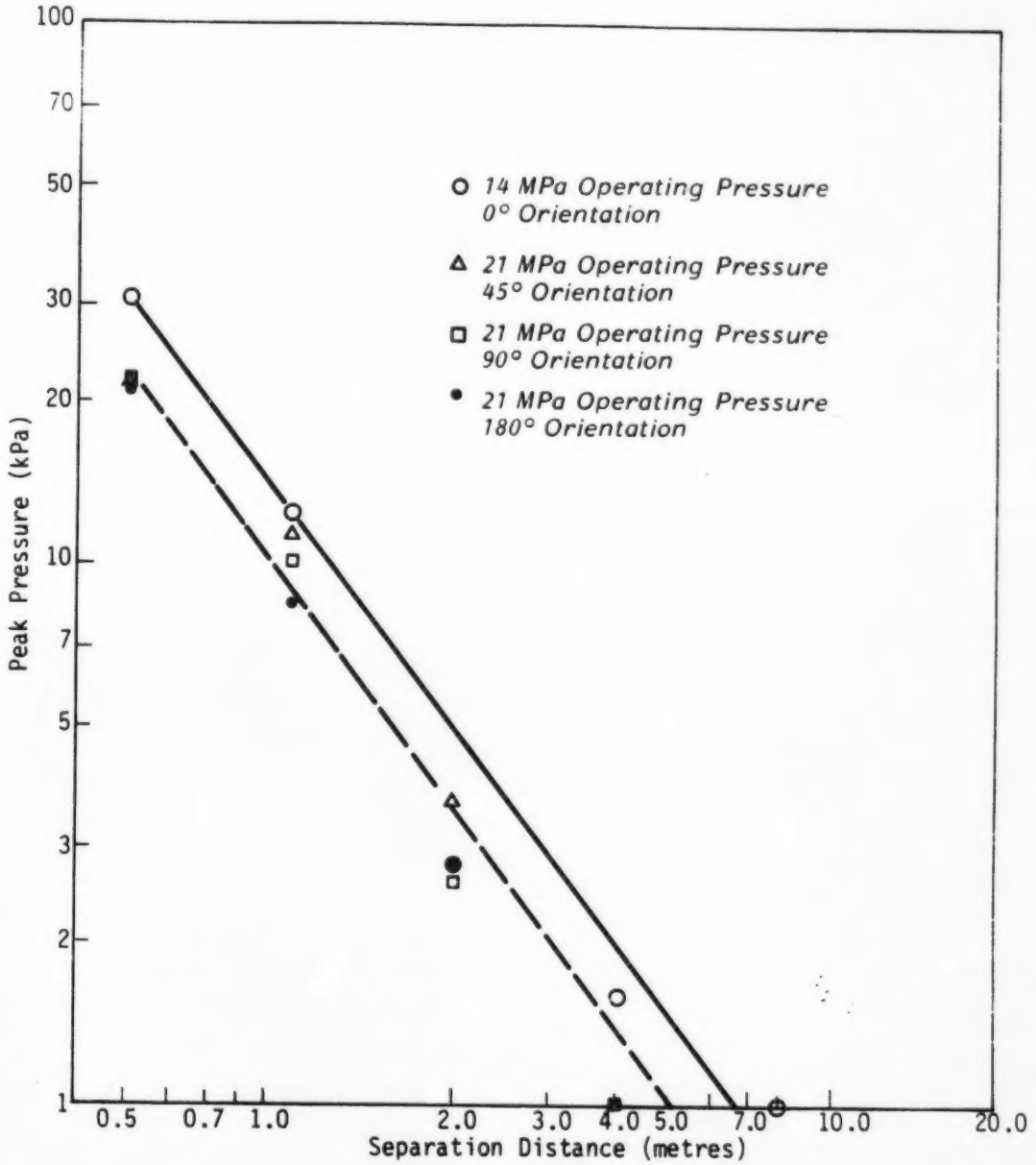


FIGURE 13

PRESSURE VS DISTANCE; TEST L1

168218 RD

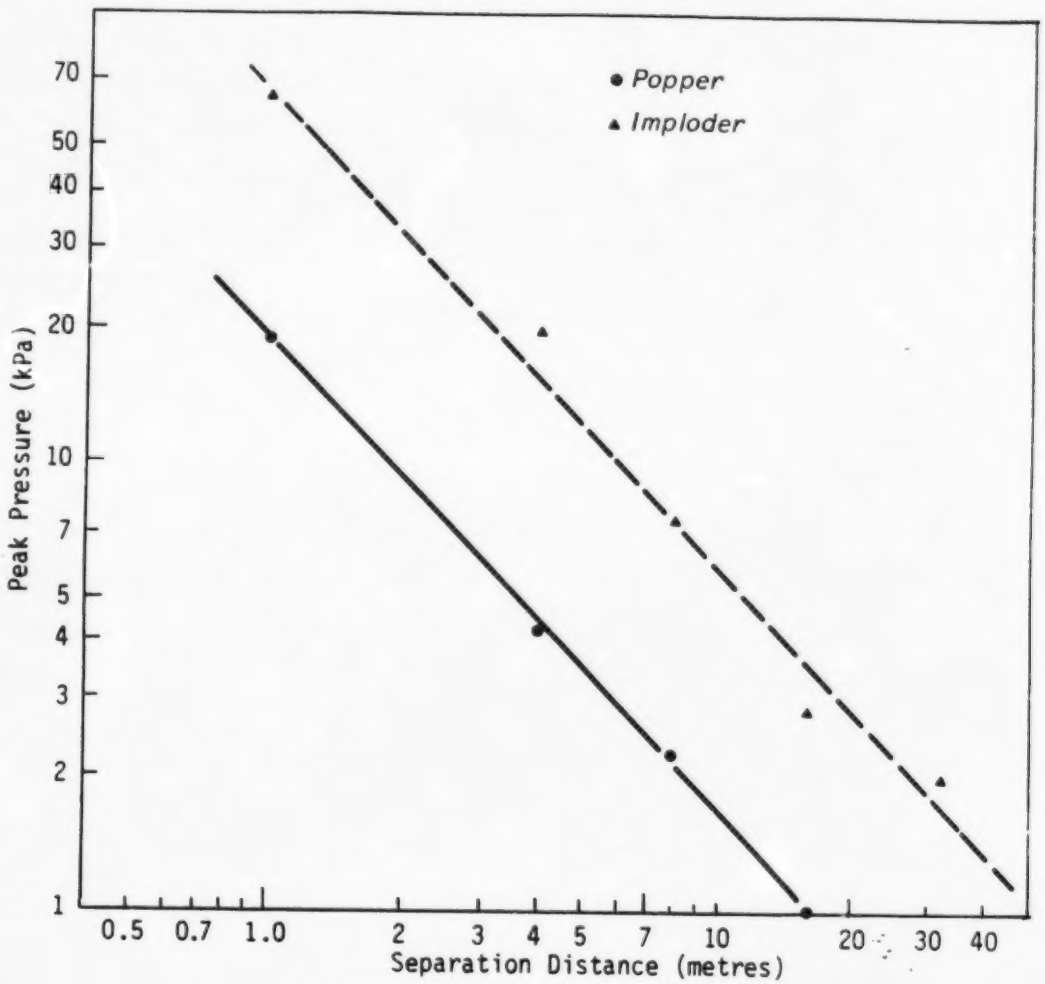


FIGURE 14
PRESSURE VS DISTANCE - TEST L2

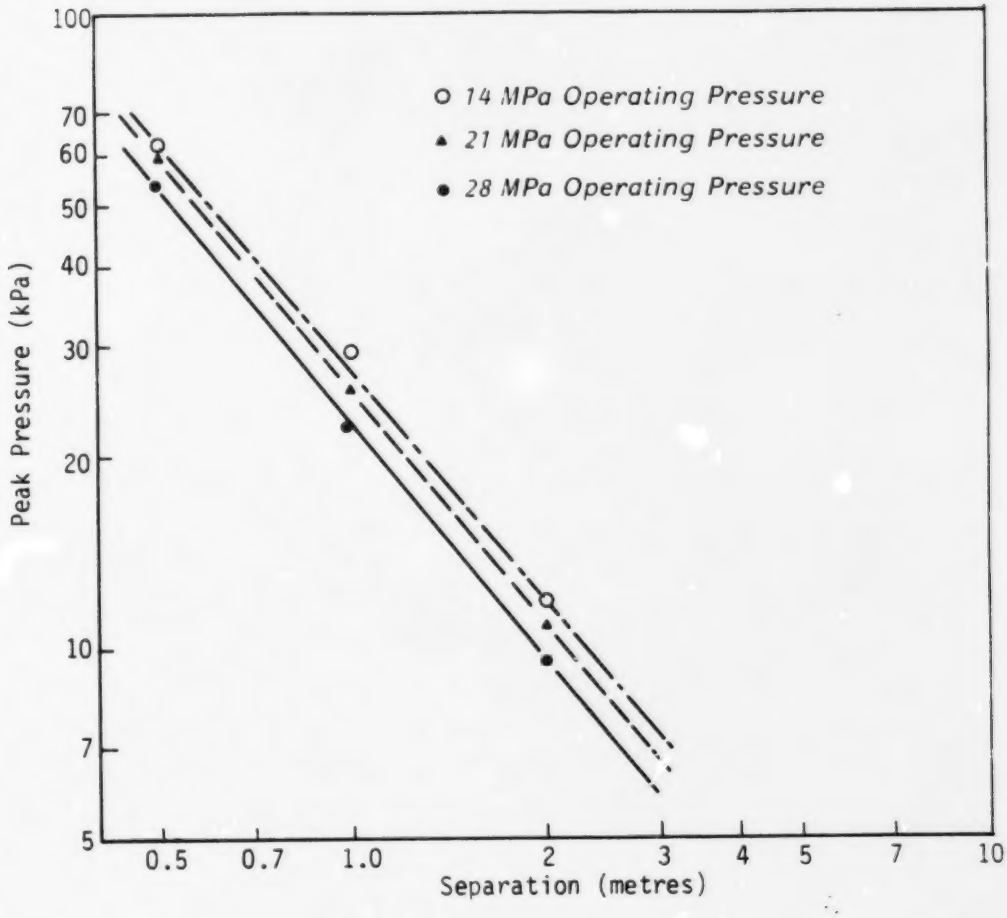


FIGURE 15
PRESSURE VS DISTANCE - TEST L3

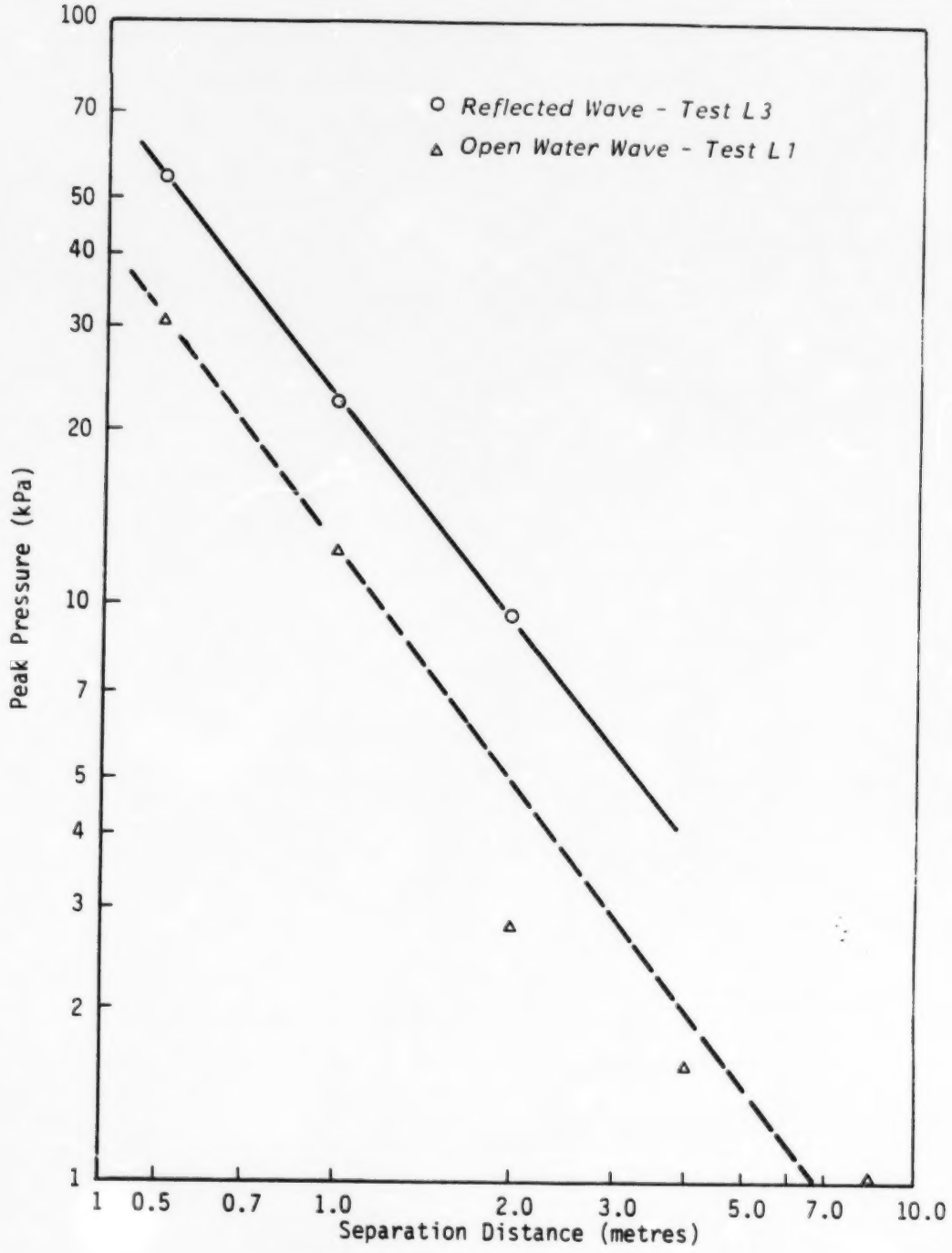


FIGURE 16

COMPARISON OF PRESSURE/DISTANCE RELATIONSHIP FOR OPEN WATER AND REFLECTED WAVES

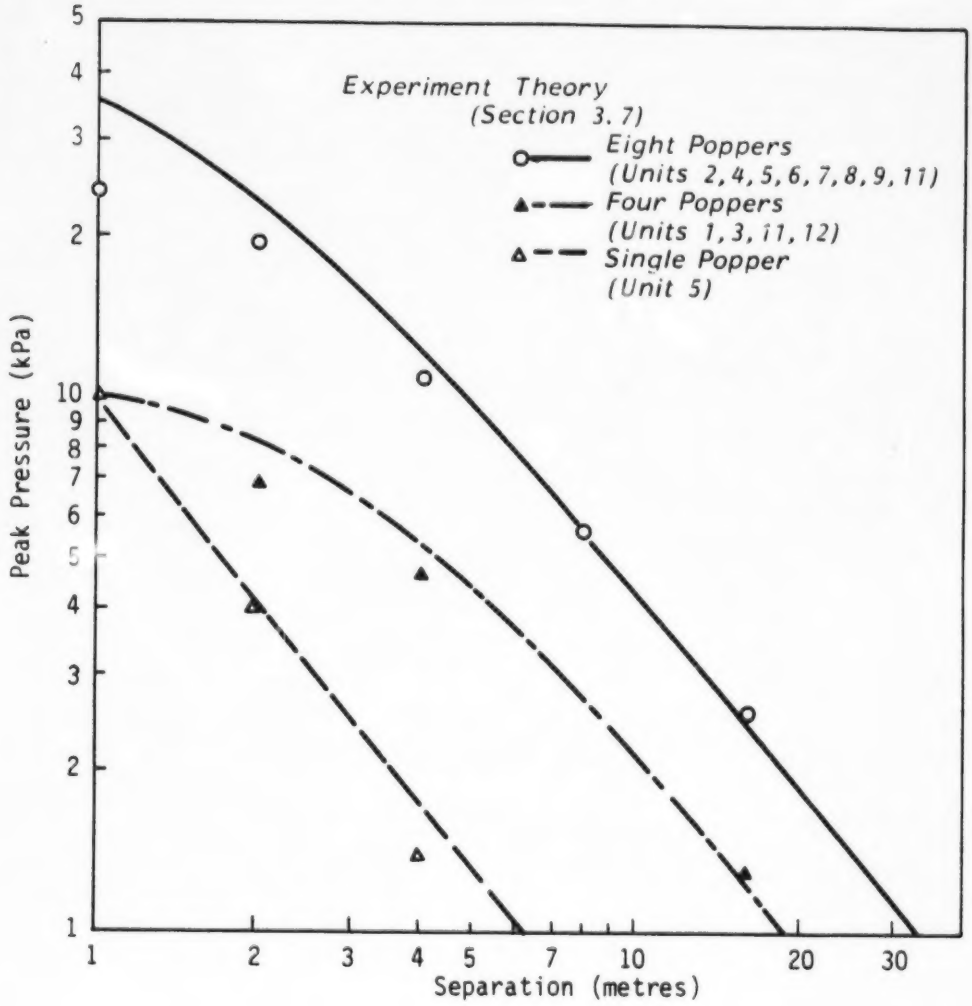


FIGURE 17

PRESSURE VS DISTANCE - TEST P1
SINGLE AND MULTIPLE POPPER OPERATION